The mechanics of brow-suspension ptosis repair: a comparative study of Fox pentagon and Crawford triangle techniques

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Meeting presentation: Part of the material has been presented at ESOPRS 2014 held on 11th-13th September 2014 in Budapest, Hungary

Financial support: EPSRC-UCL Post-doctoral Mobility Award and subsequent funding by the Dean of Engineering Sciences at University College London (UCL). Department of Health funding through the National Institute for Health Research to Moorfields Eye Hospital NHS Foundation Trust and UCL Institute of Ophthalmology for a Specialist Biomedical Research Centre for Ophthalmology.

Proprietary interest statement: The authors have no proprietary or commercial interest in any of the materials discussed in this article. No conflicting relationship exists for any author.

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Running head: Mechanics and geometry of brow-suspension surgery

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Précis: The two most commonly-used brow-suspension geometries, Fox pentagon and Crawford triangles, were compared on the basis of displacements of the inflection marks and the mechanical strains in the lines of the two geometries.

Purpose: To perform quantitative analysis of the most commonly-used brow-suspension configurations

Methods: The inflection positions for Fox pentagon and Crawford triangle configurations were marked on 49 healthy volunteers (male and female) and photographs taken in three states: “normal”, “closed”, and “raised”. The skin marks were measured vectorially with respect to the medial canthus, and displacement changes were evaluated for “normal-to–closed” (“blinking”) and from “closed-to-raised” (“eye-opening”) states. The distance between a pair of inflection marks, representing the approximate path of sling configurations, were also measured and analysed in relation to the mechanical properties of a variety of synthetic brow-suspension materials.

Results: “Blinking“ resulted in the greatest displacement in the medial eyelid incision, resulting in the greatest strain on the line connecting the medial eyelid and medial brow inflections. No significant differences in the strains for individual lines were found between the Fox and Crawford techniques, although the former shows a significantly lower overall strain in the whole loop than the latter. The displacements of some inflections and of the strains of a few lines differed significantly in men and women.

Conclusions: Within the scope of this study, the blinking action was shown to result in the maximum strain of ~40%, which lies within the elastic region of stress-strain curves for some commonly-used synthetic brow-suspension materials. No one method was statistically superior, although the Fox pentagon gave a significantly lower overall strain when the sling material was assumed to move somewhat around the inflections within a closed loop.

Eyelid ptosis describes a condition where one or both upper eyelids are lower than their usual position and it may arise from myogenic, aponeurotic, traumatic, mechanical or neurogenic causes. Treatment of ptosis is indicated where vision is impaired, where there is an undesired "tired" appearance, or where the droop causes headaches; severe ptosis in infants can lead to sensory-deprivation amblyopia. The appropriate treatment is dependent on patient age, severity of ptosis, and the power of the levator palpebrae superioris (LPS; "levator") muscle that elevates the upper eyelid.[1-3]

Brow-suspension surgery is usually performed for severe ptosis (> 4mm of droop relative to the "normal") where levator function is poor (< 4mm) or absent.[1,4] Using various materials – either biological (fascia lata) or synthetic polymers (such as silicone rods, polypropylene thread or polyester mesh)[1,3,5] – the upper eyelid is connected to the mobile tissues of the forehead (frontalis muscle) through the subcutaneous plane; the upper eyelid is then opened by the patient raising their eyebrow. Various patterns have been described for the subcutaneous passage of the suspension material, such as a single triangle,[6,7] a pentagon (Fox pentagon),[5] a rhomboid,[8] a double trapezoid,[9] or a multiple triangular arrangement (Crawford triangles).[10,11] The Crawford triangles and Fox pentagon are the most commonly-used configurations, although without any logical reason being evident. The Fox pentagon and Crawford triangles differ both in position of the polygonal inflections (incisions; Figure 1) and also in the continuous loop used for the Fox method, as compared with the two largely independent loop systems employed with the Crawford method; the distribution of stresses within these systems might be expected to be different. Although a retrospective comparison of the two techniques has been reported,[12] to date there has never been a study of the dynamics of the inflection points for each of the techniques.

In this study, the two methods were compared by evaluating displacements of the inflection points, thereby predicting the strains in sling materials, and elucidating any difference in stresses with the two systems which may have implications for the elastomeric properties of the suspension material. The impact of geometric differences between the systems on the predicted mechanical behaviour (stress and strain relationships) of commonly-used synthetic slings was estimated using the known mechanical properties of the materials.

Methods

Forty-nine (24 male; 48%) healthy volunteers, aged between 25 and 65 years (median 41), participated in this study. Volunteers of Far-eastern origin were excluded because of their markedly different eyelid structure. The study was approved by the local research ethics committee.

The incision points for ptosis repair have been termed “inflection marks” in this paper in order to simulate the course of brow-suspension material upon implantation. Using a surgical marker-pen, the inflection marks for the Fox pentagon were marked on one closed eyelid of a comfortably-seated volunteer, and the Crawford arrangement on the other eyelid. For the Fox method, two marks were drawn at about one-third and two-thirds along 2mm above the lash line, another two placed just above the eyebrow, and the last (uppermost) mark as an equilateral triangle based on the brow marks; by being placed slightly nearer to the neighbouring canthus, the two points above the brow were more widely spaced than those on the eyelid. The inflection marks for the Crawford technique were similar, but with an extra eyelid mark being placed at the middle of the eyelid skin-crease.[1,4] All markings were performed by one of two authors (DGE 9, CP 40).

Once marked, each volunteer was asked to open their eyes and a frontal photograph of the two eyes recorded using a Canon EOS Rebel T3i digital camera at 10 megapixel resolution (“normal”); further photographs were then taken with the eyelids gently closed (“closed”) and with the eyebrows raised (“raised”). Three dynamic situations relevant to patients after brow-suspension ptosis repair were considered: changes “normal-to-closed” (termed “blinking”, Figure 1a), “normal-to-raised” (termed “brow-raising”, Figure 1c) and “closed-to-raised” (termed “eye-opening”, Figure 1b).

For each of the three photographs, the distance of each inflection mark from the medial canthus was measured in the horizontal and vertical meridia using ImageJ (Research Services Branch [RSB] software, National Institutes of Health, USA). The horizontal “white-to-white” diameter of the cornea was used as 11.7mm for calibration for each photograph.[13]

Changes in the position of the various inflection points were calculated for “blinking”, and also for “eye-opening”: For each of these scenarios, the differences in the horizontal (Δx) and the vertical (Δy) meridia for each mark were evaluated and the resultant displacements derived.

Pairs of marks appropriate to the passage of a sling material were also connected by straight lines (5 lines for Fox pentagon, 8 lines for Crawford triangles; Figure 1) and the point separation measured for each pair; from each measurement of separation, the strain was calculated for two scenarios – namely, “blinking” and “brow-raising” – by dividing the change in separation length by the original separation (expressed as a percentage). In addition to the strain calculations for each separation, the strain of the overall length associated with a closed path sling material was calculated – that is, one length (L1+L2+L3+L4+L5) for the Fox method and two lengths (L2+L3+L7 and L4+L5+L8) for the Crawford technique, to model the continuous nature of the Fox loop in contrast to two independent Crawford loops.

All of the above-mentioned displacement and strain evaluations were repeated, and the results for male and female participants considered separately.

Statistical Analysis

The displacements of points for each sling configuration, as well as for each of the two dynamic scenarios, were analysed using one-way analysis of variance (ANOVA) using the software package Origin 9.0 (OriginLab Corporation, Northampton, USA). Independent t-testing was used to compare displacements and strain with the two techniques (Fox and Crawford), and any gender difference. For all analysis, an α-risk of 0.05 was considered statistically significant.

Results

For each of the three eyelid positions, the mean distance of each inflection in the horizontal (x) and vertical (y) meridian, with respect to medial canthal datum, is illustrated in Figure 2.

Unsurprisingly, “blinking” resulted in a significant (6-8mm) displacement of the eyelid marks, but those above the brow and the apical point hardly changed, with < 0.7 mm shift in both meridia. Both eyelid points move medially during “blinking”, with the medial mark moving significantly more (approximately 2mm) than the lateral. With the Crawford arrangement, the central mark on the eyelid behaved like the medial, and the displacements for comparable markings with the Fox and Crawford techniques were not significantly different (Table 1 in Supplemental Digital Content 1 and Figure in Supplemental Digital Content 2).

On “eye-opening”, however, all marks moved laterally by varying degrees, with the forehead mark moving the least (~5 mm) and the eyelid marks moving the most (~8-10 mm). As with “blinking”, the medial mark during “eye-opening” moved ~2mm more than the lateral, and also the Fox and Crawford methods had similar displacements for the inflections (Table 1 in Supplemental Digital Content 1 and Figure in Supplemental Digital Content 2).

The estimated strains were calculated from the changes in the distance between pairs of relevant inflections. For both sling arrangements, eyelid closure resulted in extension of all individual suture lines, with the exception of those along the eyelid (line 3 for Fox; lines 3 & 4 for Crawford in Figure 1). The lines connecting the eyebrow marks to the eyelid marks (lines 2 & 4 for Fox; lines 2, 5, 7 & 8 for Crawford) resulted in strains (25-40%) an order of magnitude greater than that in other pairs (~2-6%). For both suspension methods, the maximum strain was within the line connecting the medial eyelid and medial brow inflections (Line 2), with 42.2 ± 2.1% (mean ± standard error) for Fox, and 40.4 ± 2.2% for Crawford techniques (Table 2 in Supplemental Digital Content 1).

With either configuration, raising the eyebrows reduced the spacing between the forehead mark and either of the brow marks (between -7-10% strain), whilst there was increased spacing of relevant brow and eyelid marks (with 21-27% strain). Spacing of marks within the eyelid (line 3 for Fox; lines 3 & 4 for Crawford) underwent minimal strains during “brow-raising” (< 2% for Fox; < 1% for Crawford) and, as with “blinking”, the maximum strain was achieved between the medial lid and medial brow inflections (26.8 ± 2.7% for Fox; 27.3 ± 2.6% for Crawford) (Table 2 in Supplemental Digital Content 1).

No significant difference was found between Fox and Crawford configurations when comparing individual lines between surgically relevant pairs of inflections. However, when overall strains for “blinking” is considered, strain in the Fox pentagon (16%) is significantly ($p<0.0001$) different than that within the Crawford triangles (25%). Likewise, for the “brow-raising” scenario, the Fox strain (5%) was significantly ($p<0.00005$) different from that of the Crawford method (17%) (Table 2 in Supplemental Digital Content 1).

For each of the three states of eyelid position, the inflection for the Fox pentagon and Crawford triangles are analysed separately between male and female (Figure in Supplemental Digital Content 3). During “blinking” there was a significant gender difference in the displacement of a few points, namely, the forehead and the two brow marks for the Fox method ($p = 0.01$-0.04) and the medial brow mark for the Crawford method ($p = 0.02$). During "eye-opening" with either sling technique, there was a significant gender difference for displacement of the top three marks (forehead and both brow marks), with men having ~2-3mm greater displacement (Table 3 and Table 4 in Supplemental Digital Content 1). Comparing the strains on surgically-relevant pairs of points, a gender difference was found only with the Crawford technique (lines 3 & 8 for "blinking", and lines 2, 5 & 7 for "brow-raising"). With "blinking", females had ~9% greater strains in magnitude on the mentioned lines than males (males -1% for line 3, 30% for line 8; females -10% for line 3, 39% for line 8), whilst males had ~10% greater strains for "brow-raising" (males 20-30%; females 10-20%). Similarly, when strains were recalculated for the overall sling loops, a significant difference was found between men and women for the "brow-raising" with the Crawford technique (males 22%, females 13%).

Discussion

The well-recognised infero-medial displacement of the upper lid during blink-closure has been well demonstrated by our use of inflection marks, with those on the eyelid showing most displacement (~6-8mm for "blinking" scenario and ~8-10mm for "eye-opening"). With brow-suspension repair of severe ptosis, the sling material is passed between pre-marked incision sites and evaluation of the distance between surgically-relevant marks might provide an indication of mechanical aspects and loading of the implanted materials. The two most popular configurations for brow-suspension were considered in this study, and the expected strains estimated both for individual pairs of marks and also for the overall length of suture material; the former case assuming the sling materials are fixed at each inflection point and calculating elongation of the material as the change in distance between adjacent points, whilst the latter case, which more accurately models the system, assumes that the elongation of the material is distributed throughout the knotted loop (being able to slide through inflections as a pulley system).

As reasonably expected, the magnitude of strain changes for pairs of points is positively correlated to the magnitude of displacement of points ($r=0.92$; $p<0.00001$). Owing to the greatest displacement being the medial eyelid mark (for both “blinking” and “eye-opening”), the maximum strain occurred within the line connecting this lid mark and the medial brow inflection (line 2 for both Fox and Crawford configurations), with ~40% and ~25% for “blinking” and “brow-raising” scenarios, respectively. Yield strain represents the strain at which a material starts to undergo plastic deformation. When the maximum strain values estimated in this study (~40% and ~25%) were compared with the yield strain of five commonly-used synthetic sling materials (tested at a single tensile load at 1500 mm/min displacement rate[14]; Table 1) they both were less than or equal to the yield strain for all the synthetic materials. This comparison result suggests that the maximum strain an implanted synthetic material undergoes during a blink is likely to lie within the elastic region of stress-strain curves for the five commonly-used synthetic sling materials, thereby minimising the risk of plastic deformation (and hence being able to relax back to its original length after a stretch).

Excluding Asian patients, the reported recurrence of ptosis after Fox or Crawford brow-suspension[12, 15-22] shows considerable variation, but suggests that silicone rods have a relatively low recurrence at longer follow-up intervals.

The Fox and Crawford configurations differ in both the number of sling materials and the number of inflections but, according to Ben Simon *et al.*,[12] there is no significant difference in outcome between a single-loop method (like Fox) or double-loop design (as with Crawford). We also find no significant difference in the displacement of inflections or the strains between pairs of inflections. There was, however, a statistically significant difference between the two designs in overall strain for both “blinking” and “brow-raising”; the overall strain for “blinking” being 16% for Fox versus 25% for Crawford ($P < 0.0001$), and 5% for Fox versus 17% for Crawford with “brow-raising” ($P < 0.00005$). This result might sensibly be expected since, for any single loop of sling material, the pentagon has two more sides (as compared with a triangle) along which to distribute the material loading. These findings suggest that the Fox pentagon might be a better design for distribution of load within the sling material.

An additional finding concerns the contribution of the upper brow fixation points. Whilst these points do not move from during “blinking”, they do contribute movement from the “closed-to-raised” (“eye-opening”) positions, and therefore may not be necessary in the former case. However, they may be important, even as static points for the Fox pentagon configuration, as they increase the total path length of the suspension material – this decreases the proportion of elongation and, thereby, reduces strain.

Although some small gender differences in the displacement of inflections (and, secondarily, estimated strains), these are of no clinical significance: the significant difference found with inflection displacements during “blinking” probably arises due to the very small values, which were < 0.5 mm for most of the inflection points for both horizontal (Δx) and vertical (Δy) directions; with such values, even a small gender difference (like < 1 mm) in displacements would result in a significant difference. The different displacements of inflections during “blinking” did not, however, lead to significantly different strains within related suture lines, with the exception of small gender differences in the central-to-medial eyelid line (Line 3; Figure 1) and the outer forehead line (Line 8; Figure 1) for the Crawford technique; in these lines, females exhibited slightly greater strains, and this might be related to the significantly greater palpebral aperture in women.[23] In the case of “eye-opening”, the significantly greater displacement of the three upper inflection marks on the forehead in men might be due to gender difference in facial size – men generally have larger and wider faces,[24] and might reasonably be expected to have proportionally greater excursions for any surface mark. Although the different displacements were observed for both Fox and Crawford markings, this resulted in only minor differences in strains along a few suture lines (Line 2, 5 & 7), with males having slightly greater strains.

This study analysed Fox pentagon and Crawford triangles configurations through metric data from inflection marks in the suspensory materials, although it has some limitations due to assumptions made in the analysis. First, all the inflection marks were assumed to be co-planar, thereby ignoring the 3-dimensional curvature from the forehead to the eyes; this assumption is probably of no major impact, however, as shift in the antero-posterior direction is probably minor as compared to those measured in the coronal plane. Secondly, the sling materials for ptosis correction are woven in the sub-orbicularis plane[1] and it is assumed that there is only negligible movement between this tissue plane and the overlying skin. Thirdly, the assumed maximum strains for this study were compared to estimates for commonly-used synthetic materials, these estimates being obtained by conducting a tensile test at 1500 mm/min in dry conditions; on implantation, however, sling materials might actually experience stretching velocities an order of magnitude higher under physiological conditions[25]; more sophisticated test conditions would be needed to overcome these limitations. Moreover, the comparison did not consider the *in-vivo* response to implantation of synthetic materials, such as foreign body reaction and the acute or chronic inflammatory response.[26,27] These responses are most likely to have an impact on the mechanical properties of sling materials, possibly altering their long-term efficacy. Finally, this study did not explore different ethnicities and this might be investigated further in future.

The current use of different brow suspension geometries and suspension materials is based on historical and empirical factors, rather than an evidence-based and theoretical approach to design. These limitations are reflected by the high recurrence rates and failures reported in the literature.[12,21] This study provides a good comparison between the two sling designs and an indication of the mechanical behaviour that might occur with various sling materials. This modelling approach may be of use to clinicians in planning surgery and improve outcomes for patients

Acknowledgements: This study was supported by an EPSRC-UCL Post-doctoral Mobility Award to the authors and subsequent funding by the Dean of Engineering Sciences at University College London (UCL).

DGE and GER acknowledge Department of Health funding through the National Institute for Health Research to Moorfields Eye Hospital NHS Foundation Trust and UCL Institute of Ophthalmology for a Specialist Biomedical Research Centre for Ophthalmology.

The sponsors or funding organizations had no role in the design or conduct of this research and any views expressed in this publication are solely those of the authors.

The photographic data of the participants like Figure 1 cannot be released since they are personal. However, the raw data obtained from the photographs are available at the link: https://www.repository.cam.ac.uk/handle/1810/248992. The data were used to prepare for Figure 2 and all the supplemental digital contents in this paper.

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Figure 1 Brow suspension inflection points marked on a volunteer at ‘normal’ rest: the right-hand side has the Crawford triangles configuration and left-hand has markings for the Fox pentagon. The path of sling materials for each procedure is shown by connecting pairs of relevant incision marks and numbered from medial to lateral side.

Three dynamic situations relevant to patients after brow-suspension ptosis repair (a) “Blinking” (b) “Eye-opening” (c) “Brow-raising”

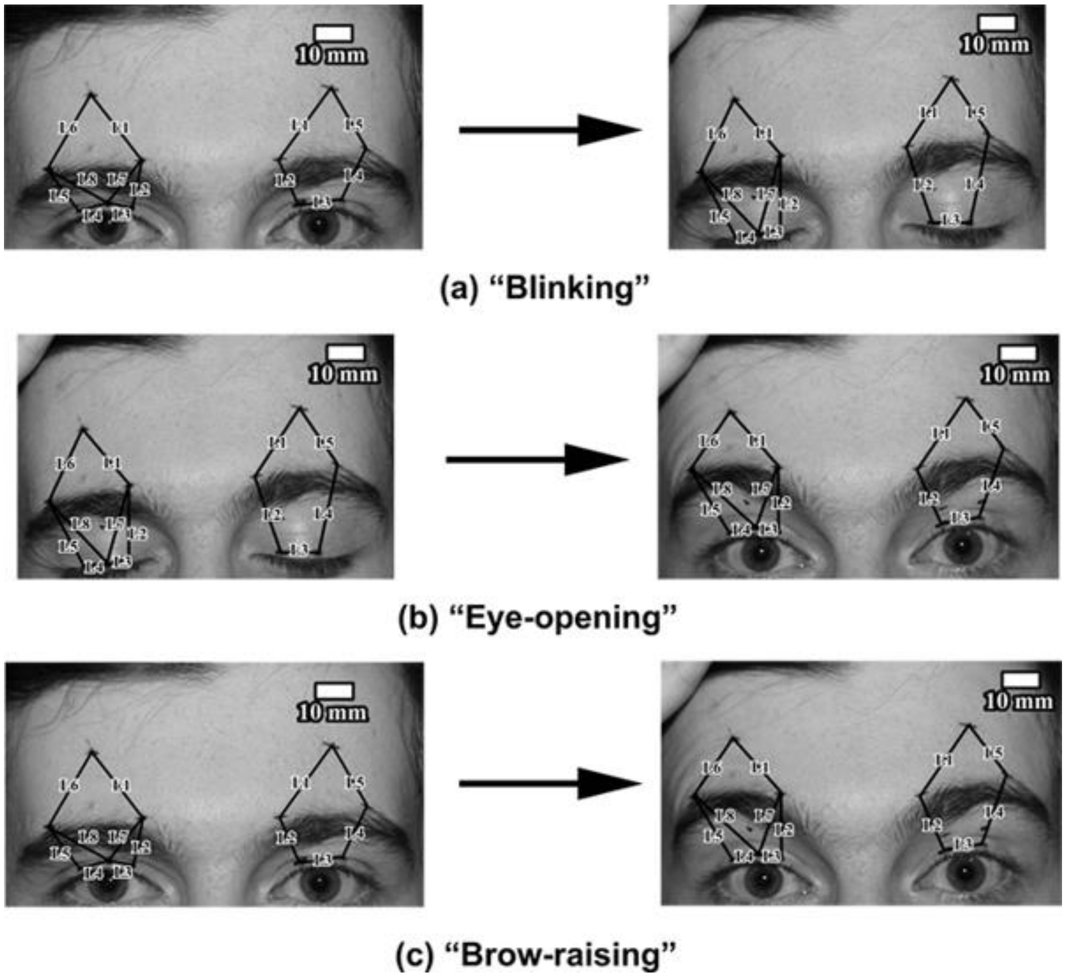
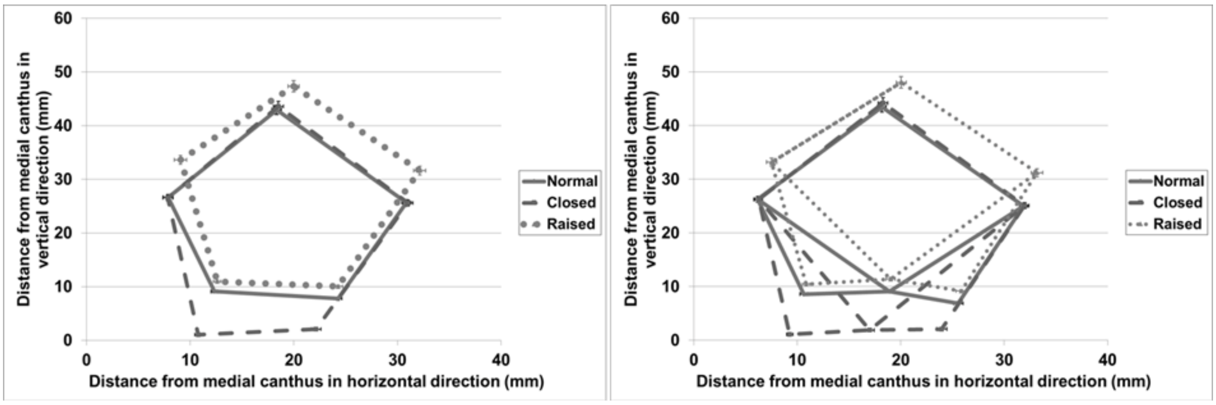


Figure 2 Graphical representation of inflection points for three states of eye-opening with two methods for brow-suspension ptosis repair. The three states were with the eyelids open ("normal"), gentle eyelid closure ("closed") and with maximum brow elevation ("raised"). The medial canthal angle was taken as the measurement datum.



(a) Fox pentagon (b) Crawford triangles

Table 1 Yield strains of synthetic commonly-used sling materials: Prolene®, Supramid Extra® II, Visitec® Seiff frontalis suspension set, Mersilene® and Ptose-Up.

Synthetic sling materials	**Yield strain (%)**
Prolene®	73.9 ± 18.8
Supramid Extra® II	84.3 ± 9.5
Visitec® SFSS	917 ± 160
Mersilene® mesh	52.1 ± 3.3
Ptose-Up	40.9 ± 6.9

List of Supplemental Digital Content (SDC):

Supplemental Digital Content 1.dox

Table 1 A summary of the displacement of inflection points during eyelid movement for the "Blinking" scenario, and for the "Eye-opening" scenario. Values represent the mean ± standard error.

The resultant displacement was calculated by square root of the sum of the squared displacement in horizontal and vertical directions.

		Fox pentagon			**Crawford triangles**		
		Displacement in horizontal direction (mm)	Displacement in vertical direction (mm)	Resultant displacement (mm)	Displacement in horizontal direction (mm)	Displacement in vertical direction (mm)	Resultant displacement (mm)
"Blinking"	Forehead mark	0.26 ± 0.22	0.48 ± 0.28	2.23 ± 0.18	0.19 ± 0.25	0.67 ± 0.29	2.29 ± 0.21
	Suprabrow mark - medial	-0.02 ± 0.22	-0.38 ± 0.27	2.04 ± 0.20	0.12 ± 0.25	-0.26 ± 0.24	1.98 ± 0.20
	Suprabrow mark - lateral	0.17 ± 0.26	0.01 ± 0.21	1.88 ± 0.20	0.07 ± 0.21	0.14 ± 0.25	1.88 ± 0.18
	Eyelid mark - medial	-2.28 ± 0.39	-7.39 ± 0.36	8.41 ± 0.22	-2.05 ± 0.37	-6.88 ± 0.33	7.82 ± 0.22
	Eyelid mark - lateral	-2.51 ± 0.35	-4.98 ± 0.45	6.46 ± 0.33	-1.77 ± 0.44	-4.23 ± 0.44	5.88 ± 0.33
	Eyelid mark - central	N/A			-2.49 ± 0.39	-6.68 ± 0.39	7.78 ± 0.31
"Eye-opening"	Forehead mark	1.47 ± 0.34	3.75 ± 0.54	4.85 ± 0.51	1.75 ± 0.35	3.82 ± 0.58	5.06 ± 0.54
	Suprabrow mark - medial	1.23 ± 0.27	7.08 ± 0.54	7.46 ± 0.53	1.24 ± 0.35	6.92 ± 0.50	7.41 ± 0.50
	Suprabrow mark - lateral	1.12 ± 0.38	6.05 ± 0.56	6.66 ± 0.57	1.20 ± 0.43	6.15 ± 0.55	6.86 ± 0.57
	Eyelid mark - medial	1.82 ± 0.25	9.93 ± 0.27	10.24 ± 0.28	1.57 ± 0.27	9.35 ± 0.29	9.64 ± 0.30
	Eyelid mark - lateral	2.12 ± 0.36	7.96 ± 0.37	8.60 ± 0.37	1.88 ± 0.39	7.09 ± 0.31	7.82 ± 0.32
	Eyelid mark - central	N/A			2.01 ± 0.36	9.54 ± 0.32	10.03 ± 0.34

Table 2 A summary of strains in the "suture lines" for the "Blinking" scenario, and for the "Brow-raising" scenario; suture lines are numbered from medial to lateral side (as shown in Figure 1).

Values represent the mean ± standard error

	Geometry	Line number	**"Blinking"**		**"Brow-raising"**	
			Type	Strain (%)	Type	Strain (%)
Individual	**Fox pentagon**	1	Extension	3.78 ± 0.82	Contraction	9.60 ± 1.36
		2	Extension	42.2 ± 2.1	Extension	26.8 ± 2.7
		3	Contraction	4.71 ± 0.98	Contraction	1.92 ± 1.37
		4	Extension	33.1 ± 2.3	Extension	20.9 ± 2.4
		5	Extension	2.38 ± 0.73	Contraction	6.80 ± 0.96
	Crawford triangles	1	Extension	2.84 ± 0.78	Contraction	7.37 ± 1.25
		2	Extension	40.4 ± 2.2	Extension	27.3 ± 2.6
		3	Contraction	5.71 ± 1.67	Contraction	0.59 ± 1.68
		4	Contraction	3.60 ± 1.51	Extension	0.44 ± 2.56
		5	Extension	28.1 ± 2.5	Extension	21.2 ± 2.3
		6	Extension	2.18 ± 0.69	Contraction	6.99 ± 1.10
		7	Extension	25.5 ± 2.1	Extension	15.5 ± 1.9
		8	Extension	34.6 ± 1.9	Extension	18.4 ± 2.1
Overall	**Fox pentagon**	1	Extension	16.0 ± 0.9	Extension	5.69 ± 1.10
	Crawford triangles	MEDIAL	Extension	25.3 ± 1.6	Extension	17.0 ± 1.8
		LATERAL	Extension	25.7 ± 1.8	Extension	16.5 ± 1.9

Table 3 A summary of the displacement of inflection points during eyelid movement for the "Blinking" scenario, and for the "Eye-opening" scenario for Fox pentagon technique. Values represent the mean ± standard error

The resultant displacement was calculated by square root of the sum of the squared displacement in horizontal and vertical directions.

		Male			**Female**		
		Displacement in horizontal direction (mm)	Displacement in vertical direction (mm)	Resultant displacement (mm)	Displacement in horizontal direction (mm)	Displacement in vertical direction (mm)	Resultant displacement (mm)
"Blinking"	Forehead mark	0.19 ± 0.40	0.45 ± 0.49	2.70 ± 0.31	0.33 ± 0.21	0.52 ± 0.31	1.78 ± 0.17
	Suprabrow mark - medial	-0.41 ± 0.38	-0.77 ± 0.46	2.50 ± 0.35	0.35 ± 0.23	-0.01 ± 0.28	1.59 ± 0.18
	Suprabrow mark - lateral	0.15 ± 0.49	0.07 ± 0.33	2.30 ± 0.35	0.19 ± 0.20	-0.04 ± 0.28	1.49 ± 0.16
	Eyelid mark - medial	-2.98 ± 0.70	-6.22 ± 0.60	8.02 ± 0.35	-1.61 ± 0.32	-8.51 ± 0.25	8.79 ± 0.26
	Eyelid mark - lateral	-2.75 ± 0.63	-3.56 ± 0.73	5.89 ± 0.55	-2.27 ± 0.35	-6.34 ± 0.40	7.02 ± 0.35
	Eyelid mark - central	N/A					
"Eye-opening"	Forehead mark	1.79 ± 0.60	4.66 ± 0.93	6.01 ± 0.86	1.17 ± 0.34	2.87 ± 0.55	3.74 ± 0.49
	Suprabrow mark - medial	1.77 ± 0.45	8.40 ± 0.91	8.96 ± 0.86	0.71 ± 0.30	5.81 ± 0.50	6.03 ± 0.50
	Suprabrow mark - lateral	1.66 ± 0.64	7.21 ± 0.85	7.96 ± 0.87	0.61 ± 0.43	4.93 ± 0.67	5.41 ± 0.67
	Eyelid mark - medial	2.02 ± 0.35	10.22 ± 0.43	10.55 ± 0.43	1.63 ± 0.38	9.65 ± 0.34	9.94 ± 0.36
	Eyelid mark - lateral	2.32 ±0.55	8.01 ± 0.61	8.73 ± 0.62	1.92 ± 0.47	7.90 ± 0.44	8.48 ± 0.42
	Eyelid mark - central	N/A					

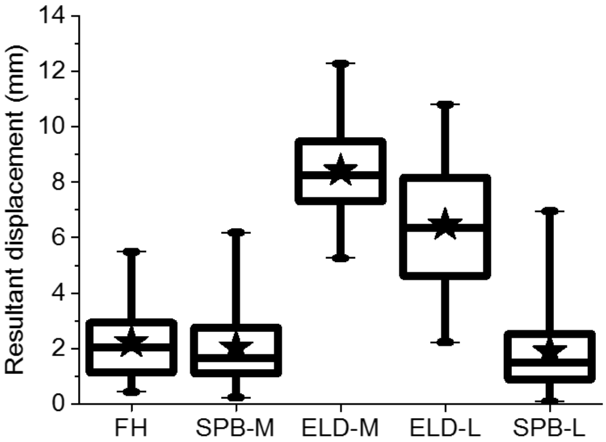
<u>Table 4</u> A summary of the displacement of inflection points during eyelid movement for the "Blinking" scenario, and for the "Eye-opening" scenario for Crawford triangle technique. Values represent the mean ± standard error

The resultant displacement was calculated by square root of the sum of the squared displacement in horizontal and vertical directions.

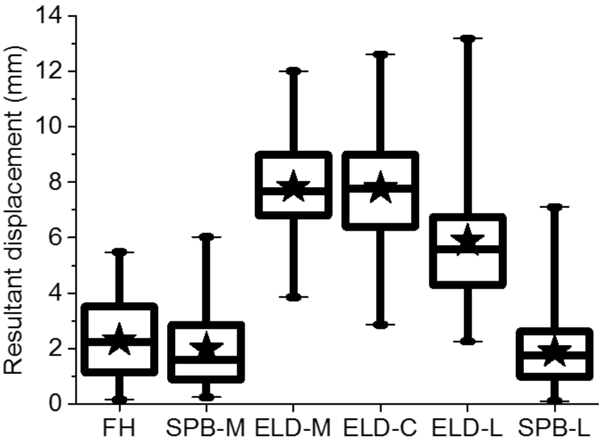
		Male			**Female**		
		Displacement in horizontal direction (mm)	Displacement in vertical direction (mm)	Resultant displacement (mm)	Displacement in horizontal direction (mm)	Displacement in vertical direction (mm)	Resultant displacement (mm)
"Blinking"	Forehead mark	0.24 ± 0.43	0.53 ± 0.46	2.62 ± 0.33	0.15 ± 0.26	0.81 ± 0.35	1.98 ± 0.24
	Suprabrow mark - medial	0.19 ± 0.44	-0.70 ± 0.39	2.46 ± 0.33	0.04 ± 0.24	0.17 ± 0.28	1.51 ± 0.21
	Suprabrow mark - lateral	0.09 ± 0.38	-0.04 ± 0.40	2.15 ± 0.33	0.06 ± 0.21	0.30 ± 0.29	1.63 ± 0.16
	Eyelid mark - medial	-2.95 ± 0.63	-5.81 ± 0.50	7.47 ± 0.26	-1.19 ± 0.35	-7.90 ± 0.33	8.16 ± 0.34
	Eyelid mark - lateral	-1.91 ± 0.53	-3.36 ± 0.69	5.28 ± 0.44	-1.65 ± 0.71	-5.06 ± 0.52	6.46 ± 0.46
	Eyelid mark - central	-2.87 ± 0.64	-5.70 ± 0.55	7.27 ± 0.43	-2.13 ± 0.45	-7.63 ± 0.48	8.27 ± 0.44
"Eye-opening"	Forehead mark	2.10 ± 0.58	5.17 ± 0.92	6.23 ± 0.92	1.40 ± 0.41	2.52 ± 0.62	3.94 ± 0.50
	Suprabrow mark - medial	1.26 ± 0.62	8.42 ± 0.81	8.95 ± 0.84	1.23 ± 0.37	5.47 ± 0.42	5.94 ± 0.39
	Suprabrow mark - lateral	1.77 ± 0.71	7.73 ± 0.86	8.49 ± 0.92	0.64 ± 0.48	4.63 ± 0.57	5.29 ± 0.55
	Eyelid mark - medial	1.99 ± 0.37	9.41 ± 0.41	9.76 ± 0.43	1.17 ± 0.38	9.29 ± 0.42	9.53 ± 0.43
	Eyelid mark - lateral	2.43 ± 0.53	7.15 ± 0.49	7.97 ± 0.49	1.36 ± 0.57	7.04 ± 0.40	7.68 ± 0.42
	Eyelid mark - central	2.29 ± 0.52	9.56 ± 0.43	10.10 ± 0.48	1.75 ± 0.49	9.52 ± 0.47	9.96 ± 0.49

Supplemental Digital Content 2.tiff

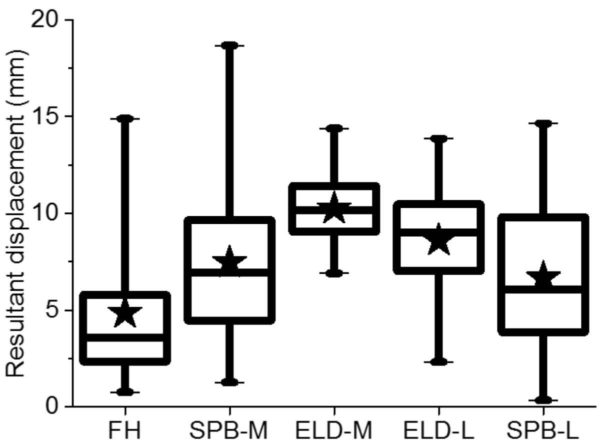
Box-plots of the resultant displacements for each inflection point: “Blinking” scenario for (a) Fox pentagon and (b) Crawford triangles. “Eye-opening” scenario for (c) Fox pentagon and (d) Crawford triangles. The box represents the quartiles (1st (=Q1), 2nd (=median) and 3rd (=Q3)), and the bars represent the minimum and maximum values measured. The star on the box-plot represents the mean value. Inflection points denoted by: “FH” forehead, “SPB-M” suprabrow medial, “ELD-M” eyelid medial, “ELD-L” eyelid lateral, “ELD-C” eyelid central, “SPB-L” suprabrow lateral.



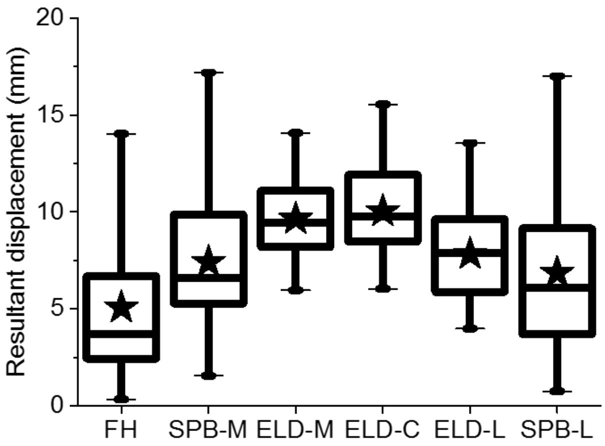
(a) “Blinking” – Fox Pentagon



(b) “Blinking” – Crawford Triangles



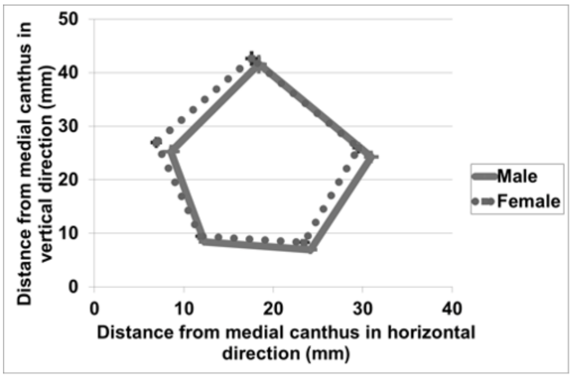
(c) “Eye-opening” – Fox Pentagon



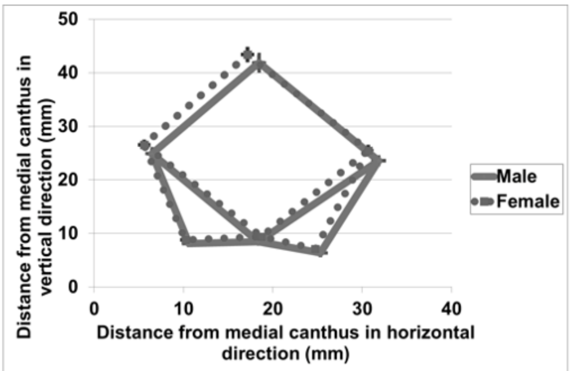
(d) “Eye-opening” – Crawford Triangles

Supplemental Digital Content 3.tiff

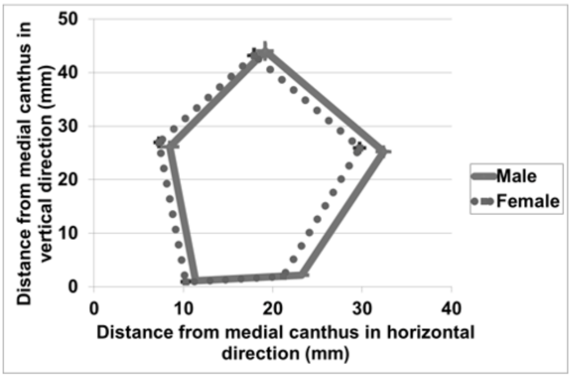
Gender variations for the inflection marks with various states and brow-suspension techniques. (a) Fox and (b) Crawford methods with lids opened normally; (c) Fox and (d) Crawford methods with eyes gently closed; (e) Fox and (f) Crawford methods with maximal brow-raising. The medial canthal angle was taken as the datum.



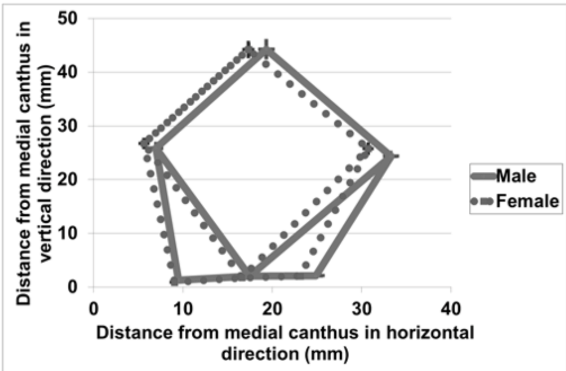
(a) Fox pentagon - Normal state



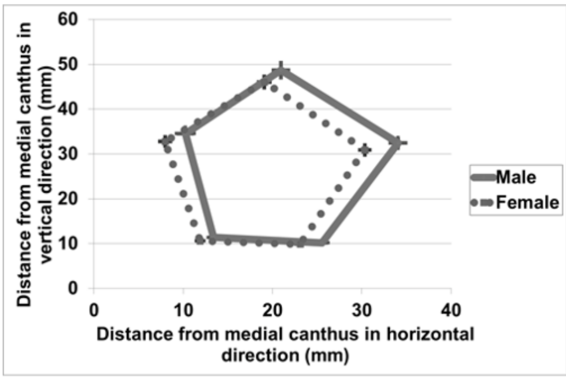
(b) Crawford triangles - Normal state



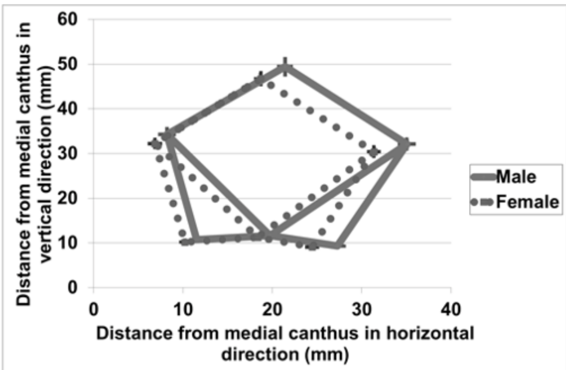
(c) Fox pentagon - Closed state



(d) Crawford triangles – Closed state



(e) Fox pentagon - Raised state



(f) Crawford triangles - Raised state